

Where Are The Young Pulsars ?

Arnon Dar

Department of Physics and Space Research Institute
Technion, Haifa 32000, Israel

ABSTRACT

We show that young pulsars with normal magnetic fields, which are born as fast rotating neutron stars (NSs) in Type II/Ib supernova explosions, can slow down quickly by relativistic particles emission along their magnetic axis. When they slow down sufficiently, they can undergo phase transitions and collapse to strange stars, quark stars or black holes in explosions that remove a substantial fraction of their initial angular momentum. The newly born strange or quark stars continue to cool and spin down very quickly as soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) to become slowly rotating, radio-quiet, dim X-ray pulsars or stellar black holes, depending on their initial mass. It can explain the apparent dearth of young radio pulsars in SNRs and in the Galaxy.

Subject headings: pulsars, soft gamma ray repeaters, anomalous X-ray pulsars, strange stars, quark stars, black holes

1. Introduction

It is widely believed that neutron stars (NSs) which are born in Type II/Ib supernova explosions (SNeII) of massive stars are rapidly rotating neutron stars (NSs) with large magnetic fields, that are spinning down by magnetic dipole radiation of their rotational energy (e.g. Shapiro and Teukolsky 1983). Such Crab-like pulsars and their accompanying supernova remnants (SNRs) are expected to be highly visible for tens of thousands of years. The mean rate of SNeII in our galaxy has been estimated to be $R \approx 1/50$ y (Tamman and Van den Bergh 1991). It is consistent with the 220 known young Galactic SNRs (Green 1998) if, on the average, they are observable for $\sim 10^4$ y. Less than 30% of the SNRs are Type I SNe remnants (Tamman and Van den Bergh 1991) which do not produce NSs. But, despite detailed radio searches, only < 20 radio pulsars out of over 1100 detected radio pulsars (Camilo et al. 1999) were found within/near young SNRs and some of them can be

due to chance overlap (Gaensler and Johnston 1995). So where are all the young pulsars born in Galactic SNRs?

Traditional arguments invoking beaming, large natal kick velocities and direct collapse to black holes have become less compelling with the accumulating results from new surveys. Thus, an alternative explanation for the apparent dearth of radio pulsars seems to be needed. Gotthelf and Vasisht (1999) have suggested that newly born Crab-like NSs with a typical surface magnetic field, $B \sim 10^{13}$ Gauss, are rare, while the majority are born as magnetars - neutron stars with huge surface magnetic fields, $B \sim 10^{15}$ Gauss (Duncan and Thompson 1992; Thompson and Duncan 1993, 1995, 1996). Their enormous magnetic field provides a natural mechanism for braking these pulsars and spinning them down very quickly. Such pulsars become unobservable in the radio in a very short time due to their slow rotation and/or the fast decay of their magnetic field. Their suggestion was motivated by the claimed success of the magnetar model for soft gamma ray repeaters (SGRs) (e.g., Kouveliotou et al. 1998; Kouveliotou et al. 1999) and anomalous X-ray pulsars (e.g., Gotthelf et al. 1999): The 4 known SGRs and the 6 known AXPs are all slowly rotating ($P=5-12$ s) pulsars, surprisingly young, as evident from the fact that all the 4 known SGRs and 3 out of the 6 known AXPs are found in/near young SNRs (Cline et al. 1982; Kulkarni and Frail 1993; Vasisht et al. 1994; Gotthelf & Vasisht 1997; Hurley et al. 1999b,c; Parmar et al. 1998; Gaensler et al. 1999). Their rotational energy is too small to power either their persistent X-ray emission or the repeated gamma ray bursts from SGRs. They spin down very quickly at a rate $\dot{P} \sim 10^{-10} - 10^{-12}$, too large to be explained by magnetic braking due to $B \leq 10^{13}$ Gauss surface magnetic fields of ordinary radio pulsars. The huge magnetic fields of magnetars can explain both the fast spin-down rate and the power source of SGRs and AXPs.

However, the magnetar model for SGRs faces severe problems (Dar 1999; Dar and DeRújula 1999a). It faces an ‘age problem’ - the magnetic spin-down ages of SGRs, $\tau_s \leq P/2\dot{P}$, are much shorter than the ages of the expanding SNRs from their birth. It also faces a ‘separation problem’ - the SGRs are found at distances too far from the centers of the SNRs where they were born, if their magnetic spin down age is their true age and their natal kick velocity is like that of ordinary pulsars, $v_{\perp} \sim 350 \pm 70$ km s $^{-1}$ (e.g., Lyne and Lorimer 1994; Toscano et al 1999). Moreover, the magnetar model of SGRs and AXPs also faces an ‘energy crisis’: Magnetic braking implies that their spin-down rate is proportional to the square of their surface magnetic field. If the energy source of SGRs is their magnetic field energy, $E_m \approx B^2 R^3 / 12$, then increase in their spin-down rate implies similar increase in their magnetic field energy. Consequently, the large increase (more than doubling) in the spin-down rate of SGR 1900+14 during its intensive burst activity around August 27, 1998 (e.g., Marsden et al. 1999; Woods et al. 1999) implies a similar increase in its huge magnetic

field energy without a plausible source. Furthermore, although the surface magnetic field of AXP 1E 2259+586 that was inferred from its observed spin-down rate yields magnetic field energy much larger than its rotational energy, it is not enough to power its steady X-ray luminosity, $L_X \approx 8 \times 10^{34} \text{ erg s}^{-1}$, over its characteristic age, $\tau_s \sim 1.5 \times 10^5 \text{ y}$. Its inferred large magnetic field (Thompson & Duncan 1993) is also inconsistent with the absorption features observed by ASCA in its X-ray spectrum (Corbet et al. 1995), if they are interpreted as cyclotron lines.

In view of the above difficulties of the magnetar model of SGRs and AXPs, here we show that an alternative solution to the SGR and AXP puzzles suggested by Dar (1999) and Dar and DeRújula (1999a) can also explain the dearth of young pulsars in SNRs and in the Galaxy. We show that young Crab-like pulsars that are born in Type II/Ib supernova explosions as fast rotating NSs with ordinary magnetic fields, slow down quickly by relativistic particle emission along their magnetic axis. When they have spun down sufficiently, they undergo a phase transition and collapse to strange stars (SSs) or quark stars (QS) which appear as SGRs and AXPs. The ejecta from the explosion, removes a substantial fraction of their initial angular momentum. The gravitational energy release, while they are cooling and contracting, powers both their quiescent X-ray emission and their star quakes which produce ‘soft’ gamma ray bursts (Ramaty et al. 1980; Cheng et al. 1996). Relativistic particle emission (RPE) in the form of jets along their magnetic axis spins them down very quickly into slowly rotating, radio-quiet, dim X-ray pulsars or stellar black holes while they are still in/near the SNR. Sensitive X-ray searches may find these slowly rotating radio-quiet, dim X-ray pulsars or black holes in/near many young SNRs.

2. Spin Down of Fast Rotating Pulsars

A spinning NS with a radius R , an angular velocity $\Omega = 2\pi/P$, and a magnetic moment misaligned from the spin axis by an angle α , radiates electromagnetic energy at a rate (see, e.g., Shapiro and Teukolsky 1983),

$$\dot{E} = \frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}, \quad (1)$$

where B_p is the magnetic field strength at the magnetic poles. Thus, braking the rotation of SGRs by magnetic dipole radiation requires a surface magnetic field

$$B_p = \left(\frac{6c^3 I}{R^6 \sin^2 \alpha} \right)^{1/2} \sqrt{P\dot{P}}, \quad (2)$$

where I is their moment of inertia. For a neutron star with a canonical mass of $1.4M_\odot$ which is supported by the pressure of a non-relativistic degenerate Fermi gas of neutrons,

$I \approx 10^{45} \text{ gm cm}^2$. Consequently, if the Crab pulsar has the canonical I and if it is slowing down by magnetic dipole radiation, then $B_p \approx 8 \times 10^{12}/\sin\alpha$ Gauss and its spin-down age is $\leq \tau_s = P/2\dot{P} \approx 1270 \text{ y}$, which is in good agreement with its birth date, 1054 AD. This agreement has been considered as compelling evidence for magnetic braking of Crab-like pulsars.

Because of the Ω^4 dependence, magnetic braking is a very efficient spin-down mechanism for newly born NSs. However, relativistic particles emission (RPE) can also spin down efficiently fast rotating pulsars: The dipole magnetic field of pulsars drops with distance like r^{-3} . The relativistic particles which escape out from the pulsar's magnetic poles along the open magnetic lines co-rotate with the magnetic field until they reach a distance

$$r_e \approx \left(\frac{cB^2 R^6}{2L_p} \right)^{1/4}, \quad (3)$$

where their pressure becomes comparable to the magnetic pressure. But, for fast rotating pulsars with normal magnetic fields, $r_e \sin\alpha$ becomes larger than the radius of the light cylinder $r_c = c/\Omega$ (e.g., for particle luminosity $L_p \approx 10^{37} \text{ erg}$, $r_e > r_c$ for $P < 100 \text{ ms}$). In that case, relativistic particles of mass m , Lorentz factor γ and energy $\epsilon = \gamma mc^2$ that stop co-rotating with the pulsar at the light cylinder carry an angular momentum $l = \gamma m c r_c = \epsilon/\Omega$. The rate of angular momentum loss by emission of relativistic particles is then $\dot{L} \approx L_p/\Omega$. Since $E_r = I\Omega^2/2$ and $L = I\Omega$, one obtains that $\dot{E}_r = I\dot{\Omega}\Omega = L\Omega$, i.e.,

$$\dot{E}_r = L_p, \quad (4)$$

and the spin-down time of the pulsar becomes $t_s \approx E_r/L_p$.

Relation (4) is well satisfied, for instance, by the Crab-pulsar where $\dot{E}_r = I\Omega\dot{\Omega} \approx 5 \times 10^{38} \text{ erg s}^{-1}$, provided that the power input into the Crab nebula $\approx 5 \times 10^{38} \text{ erg s}^{-1}$ (Manchester and Taylor 1977), is supplied by RPE from the Crab-pulsar. This suggests that perhaps the surface magnetic field of the Crab-pulsar (and of other young pulsars) which was inferred from its total spin-down rate have been overestimated. If most of its life the Crab pulsar was spun down by RPE with $L_p \approx 5 \times 10^{38} \text{ erg s}^{-1}$ that is inferred from the Crab nebula, and not by magnetic dipole radiation, then it was born with $P \approx 25 \text{ ms}$ and was spun down to its present $P \approx 33 \text{ ms}$ during the past 945 years. The 25 ms period coincides approximately with the observed dividing line between ordinary isolated pulsars and ‘millisecond pulsars’ which are spun up by mass accretion in binaries (e.g., Toscano et al. 1998).

3. Spin Down of SGRs and AXPs by RPE

The non thermal quiescent X-ray emission and the highly suggestive radio images (Vasisht et al. 1995; Frail et al. 1997) of SGR 1806-20 provide compelling evidence for a steady RPE (relativistic jets ?) from the SGR. A fading radio source within the localization of SGR 1900+14 has also been interpreted as a short lived nebula powered by relativistic particles ejected during the intense high energy activity of SGR 1900+14 in late August 1998 (Frail et al. 1999). The emission of relativistic particles along the magnetic axis can be a very efficient mechanism for braking slowly rotating pulsars with normal magnetic fields, for which magnetic braking is totally inefficient (for approximate treatment of pulsar braking by wind emission see, e.g., Harding et al. 1999 and references therein). Exact magneto-hydrodynamic calculations of pulsar braking by emission of relativistic particles, although desirable, is a formidable project. For our purpose, however, an approximate estimate is adequate:

The angular momentum carried by a relativistic particle that escapes the magnetic field at $r_e < r_c$ is, $l = \gamma m \Omega r_e^2 \sin^2 \alpha$. Hence, the rotational energy loss rate due to RPE with luminosity L_p is,

$$\dot{E}_r = I \Omega \dot{\Omega} \approx -B_p R^3 (L_p / 2c^3)^{1/2} \Omega^2 \sin^2 \alpha. \quad (5)$$

It yields an exponential decline, $E_r(t) = E_r(0) \exp(-t/\tau_s)$, with a characteristic time

$$\tau_s = \frac{P}{2\dot{P}} = \frac{I}{B_p R^3 \sin^2 \alpha} \left(\frac{c^3}{2L_p} \right)^{1/2}. \quad (6)$$

For typical QS parameters ($M \approx 1.4M_\odot$, $R \approx 6$ km, $B_p R^2 \approx 10^{25}$ Gauss cm²) and $L_p = 10^{37}$ erg s⁻¹, one obtains a short characteristic spin-down time, $\tau_s \sim 2000$ y, for GRBs and AXPs.

Spin-down by RPE implies an increase in the spin-down rate of SGRs during their gamma-ray bursts and radio flares which are caused, presumably, by bursts of relativistic particles and return to their quiescent spin-down rate at the end of the bursting activity. Indeed, the spin-down rate of SGR 1900+14 increased dramatically during its intensive burst activity in August 1998 (Woods et al. 1999 and references therein). After this intensive activity it returned to its ‘quiescent’ long term value prior to the start of its intensive activity as shown in Fig 1.

4. The Energy Source of SGRs and AXPs

The energy source of SGRs and AXPs can be gravitational contraction induced by cooling, spin-down and/or phase transition in pulsars (Dar 1999). A cooling and spinning-down NS may undergo a series of phase transitions (see, e.g., Shapiro and Teukolsky 1983 and references therein): Cooper pairing of neutrons in cool NS can release a fraction of MeV per pair, i.e., up to $\sim 10^{51}$ erg in NS. The NS can also undergo a phase transition to a strange star (SS) and cooper pairing of quarks in NS or SS can induce a phase transition and gravitational collapse to QS (Dar 1999; Dar and DeRújula 1999a). The contraction rate needed to power a total luminosity L is given by

$$L \approx \frac{1}{2} \frac{3(\Gamma - 1)}{5\Gamma - 6} \left(\frac{GM^2}{R} \right) \left(\frac{\dot{R}}{R} \right), \quad (7)$$

where $\Gamma = 5/3$ for a pulsar which is supported mainly by Fermi pressure of non-relativistic degenerate fermions and the factor $1/2$ is because $\sim 1/2$ of the gravitational binding energy is converted to Fermi motion. For a canonical pulsar mass $1.4M_\odot$ and a radius $R=10$ km, a contraction rate of e.g., $\dot{R} \sim 15 \mu\text{m y}^{-1}$ can power persistent luminosity of $\sim 10^{37}$ erg s^{-1} .

Although quantum chromodynamics cannot provide yet reliable equation of state of quark matter at supernuclear densities, phase transitions to strange matter and quark matter are suggested by general considerations: The pressure of cold nuclear matter at supernuclear densities is well approximated by that of degenerate Fermi gas of nucleons. The radius and central density of a self gravitating non-relativistic Fermi gas of neutrons of total baryonic mass M and zero angular momentum are given by the polytropic Emden-lane solution of the hydrostatic equation:

$$R = \left(\frac{2}{8^5 \pi^4} \right)^{1/3} \frac{h^2}{Gm_n^2} \left(\frac{M}{m_n} \right)^{-1/3} \approx 11.4 \left(\frac{M}{M_\odot} \right)^{-1/3} \text{ km}, \quad (8)$$

$$\rho_c \approx 6\bar{\rho} = \frac{9M}{2\pi R^3} \approx 1.93 \times 10^{15} \left(\frac{M}{M_\odot} \right)^{1/3} \text{ g cm}^{-3}. \quad (9)$$

However, the strangeness changing charge current reaction $ud \rightarrow su$ starts to transform neutrons at the top of the Fermi sea into Λ 's at the bottom of the sea when the neutron Fermi energy $E_F = (h^2/8m_n)(3\rho/\pi m_n)^{2/3}$ exceeds the effective $n\Lambda$ mass difference, $c^2(m_\Lambda - m_n)(1 - GM(r)/c^2r)$ where $M(r)$ is the total mass enclosed within a radius r . For NS with zero angular momentum it is satisfied for $M > 1.27M_\odot$. When the conversion $n \rightarrow \Lambda$ begins it reduces the Fermi pressure and causes gravitational contraction which accelerates the conversion and results in a gravitational collapse. The $n \rightarrow \Lambda$ conversion stops when their chemical potentials equalize, i.e., when $E_F(n) - E_F(\Lambda) = c^2(m_\Lambda - m_n)(1 - GM(r)/c^2r)$.

Because of their larger total number and smaller masses the total energy and pressure of asymptotically-free degenerate relativistic Fermi gas of quarks are higher than when they form bound nucleons. Consequently, most probably, quarks are not liberated in the dense cores of neutron stars and form there asymptotically-free degenerate Fermi gas. However, when cold nuclear matter is compressed to high nuclear densities, it may convert into a superfluid/superconducting Bose-condensate of spin zero diquarks with antisymmetric color wave function that is several times as dense (Alford et al. 1998; Rapp et al. 1998; Wilczek 1998; Berges and Rajagopal 1998). Cooper pairing of quarks reduces the Fermi pressure in the star and triggers its collapse which stops when the squeezing of the Cooper pairs increases their internal energy by more than their pairing energy (~ 100 MeV). The gravitational collapse to a strange or a diquark star results in a mildly relativistic supernova-like explosion and, possibly, in the ejection of highly relativistic jets. The slow gravitational contraction of the remnant Qs can power SGRs and AXPs (Dar 1999). The jets from the birth of Qs which happen to point in our direction may produce the short duration gamma ray bursts (GRBs) (Dar 1999). The long duration GRBs may be produced by highly relativistic jets from the birth of black holes in gravitational collapse of NSs due to mass accretion onto the proto-neutron star in supernovae explosions, or onto NS in compact binary systems (Dar and Plaga 1999, Dar and DeRújula, 1999b).

5. Observational Evidence For NS Collapse to QS?

Since quantum chromodynamics cannot provide yet a definite answer to whether spun-down pulsars undergo gravitational collapse, one must rely on observations. Indeed, in addition of being able to explain the origin of SGRs and AXPs, the gravitational collapse of spun-down pulsars to strange or quark stars offers explanations for some other puzzling observations related to pulsars and SNRs:

The steep spectra of the quiescent X-ray emission from SGRs and AXPs have been interpreted as the characteristic Wein tail of a thermal black body radiation from their surface. The Stefan-Boltzman law, $L_X = 4\pi R^2 \sigma T^4 \approx 1.3(R/10 \text{ km})^2 (T/\text{keV})^4 \times 10^{37} \text{ erg s}^{-1}$ yields effective NS surface area, $A = 4\pi R^2$, significantly smaller than that of NSs, $A_{\text{NS}} \approx 4\pi \times 10^2 \text{ km}^2$, as summarized in Table I (provided that their measured thermal X-ray emission and their distances are correct, and neglecting general relativity effects). An effective area smaller than the surface area of NS may be due to a non uniform surface temperature. But, it can also be due to the smaller radii of SSs or Qs.

Radio observations expose a vast range of SNR shapes (e.g., Whiteoak& Green 1966). While very young SNRs have an expanding geometry, most older SNRs have a distorted

and complicated appearance. Their distortion has been attributed to their expansion into an inhomogeneous interstellar medium (ISM). However, some SNRs have striking symmetry properties which require another explanation (e.g., Manchester 1987; Gaensler et al. 1998). A second explosion inside the SNR which also ejects relativistic jets along the rotation axis, can explain the puzzling morphology of many SNRs (Dar and DeRújula 1999b).

Imbalance in the momenta of oppositely ejected relativistic jets from the collapse can impart to the SSs or QSs a natal kick that may explain the observed large sky velocities of old, slowly rotating pulsars, whereas millisecond pulsars and very young pulsars, which have high angular momentum that prevents their collapse, have much smaller sky velocities (Toscano et al. 1998 and references there in). (The small velocity of millisecond pulsars may be a selection effect - only pulsars with a small natal kick velocity can remain bound in a stellar binary and spun up by mass accretion).

6. Discussion and Conclusions

RPE can spin down very efficiently pulsars with normal magnetic fields. The slowly rotating pulsars are probably much younger than inferred from magnetic braking.

Various observations suggest that SGRs and AXPs are not magnetars, but, most probably, they are young magnetized SSs or QSs formed recently by gravitation collapse of NSs due to a phase transition in Crab-like pulsars which have slowed-down sufficiently. The ejecta from the collapse can remove a substantial fraction of the angular momentum of the NSs leaving slowly rotating QSs. After their birth, gravitational contraction powers their quiescent emission and their star quakes that produce their bursting activity while they cool by radiation and spin-down very quickly by the emission of relativistic particles along their magnetic axis. After a short bursting activity, the SGRs, probably, become AXPs. When they spin down further and cool they may collapse to black holes or become radio-quiet, dim X-ray sources. Allowing for beaming and taking into consideration that SNeII produce also black holes and millisecond pulsars that are spun up in binaries, the observed number of SGRs and AXPs and their spin-down times are consistent with their being a short, early stage in the life of most of the ordinary pulsars. Their quiescent thermal X-ray emission suggests that they are much more condensed than NSs, however, more precise measurements are needed to confirm that.

Evidence for gravitational collapse of spun-down NSs to QSs or black holes may come from double bang morphologies of SNRs, from measurements of pulsar or black hole velocities in SNRs which do not point back to the center of their SNRs, and perhaps from

observations of gamma ray bursts and SNe. When the SGRs/AXPs cool and spin down they become slowly rotating, radio-quiet, X-ray dim pulsars or collapse to black holes. Most of these dim pulsars or black holes, probably, are still present near/in their SNRs. Sensitive X-ray searches are required to establish their presence there.

Because most of the ordinary pulsars spin down in a relatively short time and become radio-quiet pulsars, the number of ordinary pulsars that have been detected in the Galaxy (~ 1000) is smaller than that estimated from their magnetic braking ages and sky velocities, by almost two orders of magnitude. Millisecond pulsars have, relatively, very small magnetic fields. Consequently, both magnetic braking and RPE cannot spin-down significantly millisecond pulsars on time scales much smaller than the Hubble time. Therefore, the sky velocities of the vast majority of ordinary radio pulsars point away from the Galactic plane while those of millisecond pulsars have already been randomized by the Galactic gravitational fields and are isotropic (e.g. Toscano et al. 1998). Sensitive X-ray searches may establish the presence of many relatively young, radio-quiet dim x-ray pulsars in the Galaxy.

Acknowledgements: Helpful discussions, suggestions and comments by Alvaro DeRújula and the kind assistance of Shlomo Dado are gratefully acknowledged.

REFERENCES

- Alford, M. et al. 1998, Phys. Lett. B422, 247
Berges, J. & Rajagopal, 1999, Nucl. Phys. B538, 215
Camilo, F. et al. astro-ph/9911185
Cheng et al. 1996, Nature 382, 518
Cline, T. L. et al. 1982, ApJ, 255, L45
Corbet, R. H. D., et al. 1995, ApJ, 433, 786
Corbet, R. H. D. & Mihara 1997, ApJ 475, L127
Dar, A. 1999, A&A Suppl. Ser. 138 (3), 505
Dar, A. and DeRújula, A. 1999a, submitted for publication
Dar, A. and DeRújula, A. 1999b, in preparation
Dar, A. & Plaga, R. 1999, A&A 349, 259
Duncan, R. C. & Thompson, C. 1992, ApJ, 392, L9
Frail, D. A. et al. 1997, ApJ, 480, L129

- Frail, D. A. et al. 1999, *Nature*, 398, 127
- Gaensler, B. M. et al. 1998, *MNRAS* 299, 812
- Gaensler, B. M. et al. 1998, *ApJ*, 526, L37
- Gaensler, B. M. and Johnston, S. 1995, *MNRAS*, 277, 1243
- Gotthelf, E. V. & Vasisht, G. 1997, *ApJ*, 486, L133
- Gotthelf, E. V. & Vasisht, G. 1998, *astro-ph/9804025*
- Gotthelf, E. V. & Vasisht, G. 1999, *astro-ph/9909139*
- Gotthelf, E. G. et al. 1999, *ApJ*, 522, L49
- Green, D. A. 1998 <http://www.mrao.cam.ac.uk/surveys/snrs>
- Harding, A. et al. 1999, *ApJ*, 525, L125
- Hurley, K. et al. 1999a, *ApJ*, 510, L111
- Hurley, K. et al. 1999b, *ApJ*, 519, L143
- Hurley, K. et al. 1999c, *ApJ*, 523, L37
- Iwasawa, K. et al. 1992, *PASJ*, 44, 9
- Kouveliotou, C. et al. 1998, *Nature*, 393, 235
- Kouveliotou, C. et al. 1999, *ApJ*, 510, L115
- Kulkarni, S. R. & Frail, D. A. 1993, *Nature*, 365, 33
- Lyne, A. G. & Lorimer, D. R. 1994, *Nature*, 369, 127
- Manchester, R. N. & Taylor, J. H. 1977, *Pulsars*, Freeman, San Francisco, California.
- Manchester, R. N. 1987, *A&A* 171, 205
- Marsden, D. et al. 1999, *ApJ* 520 L107
- Mazets, E. et al. 1979a, *Nature* 282, 587
- Mazets, E. et al. 1979b, *Sov. Astro. Lett.* 5, 343
- Mereghetti, S. *astro-ph/9911252*
- Mereghetti, S. & Stella, L. 1995, *ApJ*, 442, L17
- Mereghetti, S. et al. 1997, *A&A*, 321, 835
- Parmar, A. et al. 1998, *A&A*, 330, 175
- Ramaty, R. et al., 1980, *Nature*, 287, 122
- Rapp, R. et al. 1998, *PRL*, 81, 53

- S. L. Shapiro and S. A. Teukolsky, 1983, *Black Holes, White Dwarfs and Neutron Stars*, John Wiley & Sons
- Sugizaki et al. 1997, PASJ, 49, L25
- Thompson, C. & Duncan, R. C. 1993, ApJ, 408, 194
- Thompson, C. & Duncan, R. C. 1995, MNRAS, 275, 255
- Thompson, C. & Duncan, R. C. 1996, ApJ, 473, 332
- Toscano, M. et al. 1999, MNRAS 307, 925
- van den Bergh, S. & Tamman, G.A. 1991 ARA&A 29, 363
- Vasisht, G. et al. 1994, ApJ, 431, L35
- Vasisht, G. et al. 1995, ApJ, 440, L65
- Vasisht, G. & Gotthelf, E. V. 1997, ApJ, 486, L129
- White, N. E. et al. 1996, ApJ, 463 L83
- Whiteoak, J. B. Z. & Green, A. J., 1996, A&AS 118, 329
- Wilczek, F. 1998, Nature 395, 220
- Woods, P. M. et al. 1999b, ApJ, 524, L55

Table 1. Anomalous X-Ray Pulsars

Pulsar	Ref.	P (s)	τ_s (yrs)	kT (keV)	L_X^a (10^{35} erg s $^{-1}$)	A_s ($4\pi \times 10^2$ km 2)
1E 1841–045	b	11.76	3.9×10^3	0.55	$3d_{7kpc}^2$	$0.25d_{7kpc}^2$
1E 2259+586	c	6.98	1.5×10^5	0.41	$0.8d_{4kpc}^2$	$0.22d_{4kpc}^2$
4U 0142+615	d	8.69	6.0×10^4	0.39	$0.7d_{4kpc}^2$	$0.24d_{1kpc}^2$
1E 1048–5937	e	6.44	4.6×10^3	0.64	$5d_{10kpc}^2$	$0.23d_{10kpc}^2$
RX J170849.0–400910	f	11.00	...	0.40	$10d_{10kpc}^2$	$0.17d_{10kpc}^2$
PSR J1844-0258	g	6.97	...	0.64	$3d_{15kpc}^2$	$0.15d_{15kpc}^2$

^aAll luminosities are in the $\sim 1 - 10$ keV energy band as corrected by Gotthelf and Vasisht 1998 for absorption.

^b Vasisht & Gotthelf 1997.

^c Corbet et al. 1995, Iwasawa et al. 1992, and refs. therein.

^d White et al. 1996, Mereghetti & Stella 1995, and refs. therein.

^e Parmar et al. 1998, Mereghetti et al. 1997, Corbet & Mihara 1997 and refs. therein.

^f Sugizaki et al. 1997.

^g Gaensler et al. 1999.

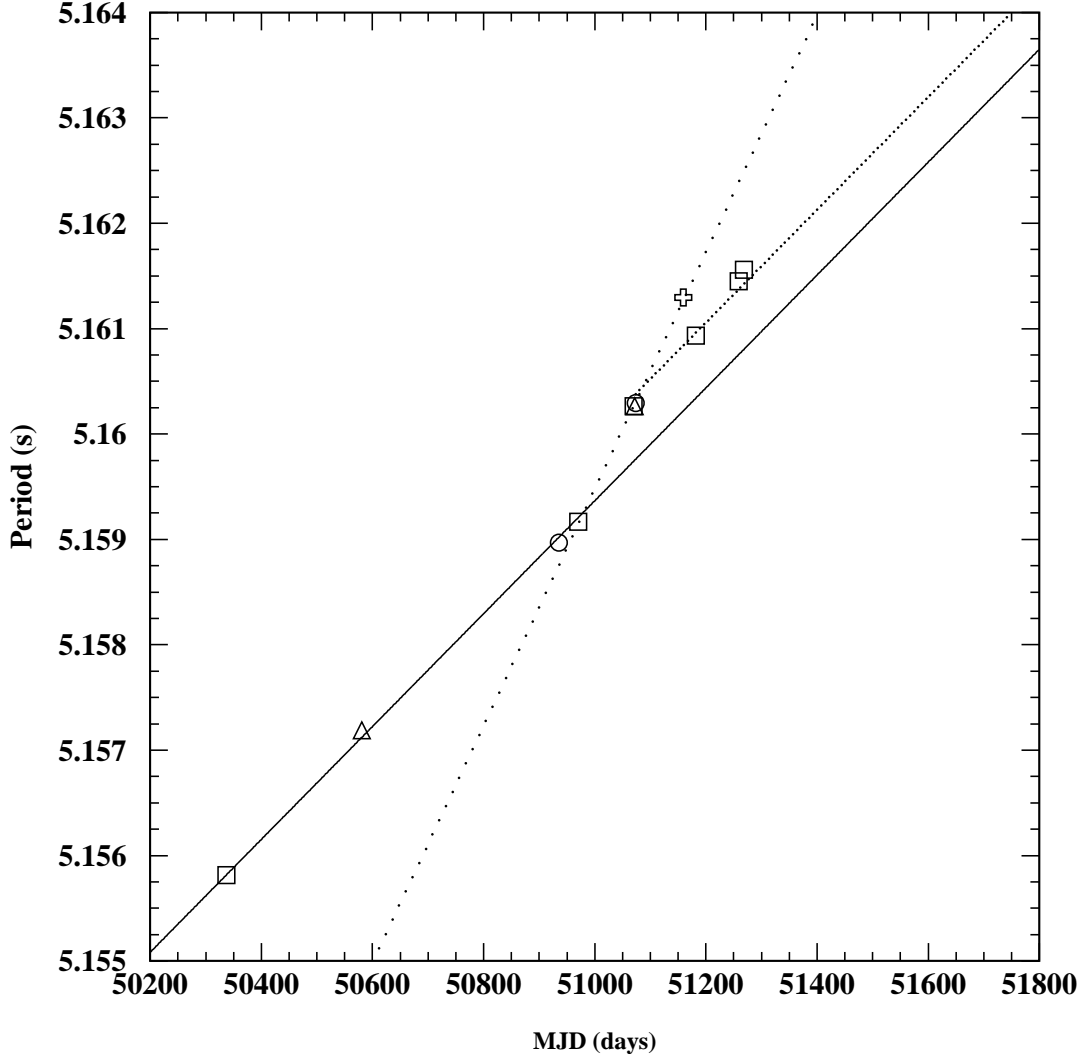


Fig. 1.— The period of SGR 1900+14 as function of time measured by RXTE (Woods et al. 1999, squares), BeppoSAX (Woods et al. 1999, triangles), ASCA (Hurley et al. 1999c; Murakami et al. 1999, circles) and BSA (Shitov 1999, cross). The lines are best linear fits to the X-ray periods of the SGR before June 9, 1998 ($\dot{P} = 6 \times 10^{-11}$), between June 9 - August 27, 1998 ($\dot{P} = 1.3 \times 10^{-10}$), and after August 27, 1998 ($\dot{P} = 6 \times 10^{-11}$). Between June 9-August 28, its ‘average’ spin-down rate has changed by a factor ~ 2.2 as a result of continuous spin-down or a sudden brake